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An Experimental Study of Abnormalities Produced in the Organism by Electricity

A New Kata-Thermometer for Hot Atmospheres and a Simplified Method for Computing

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THE JOURNAL OF INDUSTRIAL HYGIENE

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AN EXPERIMENTAL STUDY OF ABNORMALITIES PRODUCED IN THE ORGANISM BY ELECTRICITY*

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GENERAL INTRODUCTION

JEX-BLAKE (1) in his Goulstonian Lectures discussed the injuries produced by electricity; more recently Jaffé (2) has published a review of this whole subject. From these two articles a summary of general information has been prepared that introduces the experiments with which this paper deals. The reader is referred to these two papers for further information and for references to original work.

The first fatal accident with electricity followed the introduction of the dynamo in 1879 and was produced by an alternating current at 250 volts; with the rapid development of the electrical industry the number of accidents has increased, although it has not paralleled the extensive use of electricity. In 1913, 670 deaths in the United States were attributed to electricity. The ages of greatest incidence of shock are from 15 to 30, probably owing to less attention to work and less reflection in young workers. Those who work habitually with electric circuits develop a dangerous disregard for them.

Six factors must be considered when an electric accident is investigated: (1) voltage; (2) amperage; (3) duration of contact; (4) type of circuit (continuous or alternating); (5) position of the electrodes; and (6) resistance offered by the body and by the contacts.

Circuits supplying houses and factories are commonly of 110 or 220 volts, either alternating or continuous current. The opinion still prevails among many engineers and physicians that these voltages are not dangerous. This is not true, however, for a 110-volt

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circuit may prove fatal. The number of deaths due to accidents with low voltages is increasing.

With regard to the current, an irreversible stopping of the heart is produced in the dog by 70 to 80 milliamperes. For man a current (alternating or continuous) of 18 milliamperes is painful, and 20 milliamperes is bearable when the electrodes are held in the hands. For a normal person the current ought not to exceed 30 milliamperes. A current of 50 to 60 milliamperes is very dangerous, and 100 milliamperes often causes death.

The strength of an electric current in a given circuit is determined by dividing the applied voltage by the resistance of the circuit. In animal experimentation the number of amperes may easily be determined. Alternating currents are considered more dangerous than continuous; some have placed the coefficient of danger of alternating and continuous currents as 4:1. The continuous current produces electrolytic changes; the alternating current causes tetanization of the muscles and perspiration in the skin that decreases the contact resistance.

A determination of the resistance of the body to the passage of an electric current presents not only a problem of physics but a complex physiologic one. The electrical resistance is dependent on the cellular elements and is variable according to the variations in their intimate structure. It is different for the various organs and always bears a certain relation to their morphologic structure and chemical constitution. Moreover, by the effect of the electric current, heat is developed and the resistance offered by the body diminishes with the elevation of the temperature. In addition, the damage to the semipermeable membranes brings about variations in resistance. The resistance of the contacts also is a determining factor in the amount of current that flows.

The real conductors of the electric current in the body are the fluids that bathe the tissues. Blood is the best conductor and most of the current passes along the blood vessels. The greatest density of the electric current is found near the electrodes. It is important to determine not only whether vital organs are traversed by the current but also the amount of electricity to which they are exposed. This is difficult of any accurate measurement.

The skin is an especially poor conductor of electricity and the resistance is in direct proportion to the thickness of the epidermis. The possibilities of good conduction in the skin are due to the presence of sebaceous and sweat glands, with their secretion. The smaller the concentration of these glands in any area, the greater the resistance in comparison with the normal. The subcutaneous tissue, on account of its richness in blood vessels, is an especially good conductor. Fatty tissue is, in general, a poor conductor. The muscle, because of its high content of water, ranks as a good conductor, especially striated muscle if the tendons and aponeuroses are excluded. The peripheral nerves, because of their poor vascularization, are among the poor conductors. The central nervous system offers a small resistance to the current because of the high fluid content, but the mass of bone by which it is surrounded makes

the access of the current difficult. The bones offer a considerable resistance to the passage of the current; the denser the bone, the greater the resistance. If one attempts to compile a table of powers of conductivity of individual tissues, there is noticeable a parallelism with the fluid content indicated in parenthesis: muscle (75 per cent.); cerebellum (68 per cent.); bone (14 per cent.); peripheral nerves, skin, and bones (5 to 16 per cent.).

The resistance of organisms to the current is relative. At the head of the scale of animals most resistant are frogs and turtles. Horses and dogs are readily killed by relatively small quantities of electricity. Rabbits, and especially rats, are much more resistant. The rat's heart is said to recover spontaneously from the fibrillation into which it is thrown by the passage of the current. The rabbit's heart often recovers spontaneously, the guinea-pig's rarely, and the adult dog's never.

The pathologic changes produced in the tissues of the body have been summarized by Jaffé. Marked changes are found in the skin. In passing through the skin, the electric energy is transformed into heat which produces the surface markings. A free discharge causes the formation of electric sparks which give burns of the third degree. The electric marking is painless and does not show a surrounding inflammatory reaction. If the patient survives, the altered tissue breaks down slowly, presenting the picture of an aseptic necrosis without pus formation or general bodily reaction. It seems as if the defense mechanisms of the tissues had been paralyzed.

In traversing the body, electric currents cause tetanic contractions of the entire musculature. The severe contractions account for the exhaustion and the lasting pains in the muscles. Both macroscopic and microscopic changes have been described. There is a displacement of the contractile substance of the fiber, and instead of the fine cross striation, coarse, hyaline transverse bands are seen.

In high tension accidents, in which the current enters the body through the skull, lesions of the bone are common. There is sometimes a great perforation of the skull with holes in the dura mater and small channels in the brain. Necrosis occurs in less severe accidents.

The progressive character of the wounds caused by electricity seems to be due to an alteration of the blood vessels which may involve large sections of them. The walls of the blood vessels through which the current has passed are brittle and friable. The endothelium is injured and parietal thrombi are attached to the intima. The great vulnerability of the blood vessels accounts for the severe hemorrhages as complications of injuries due to electricity.

Functional alterations in the heart play an important rôle in the explanation of death from electric shock. When a low tension current passes through the heart, complete inhibition takes place. There are incoordinate contractions of separate muscle bundles of the ventricles; this fibrillation is produced by the direct action of the current on the muscle fibers and ganglion cells of the heart. When a high tension current is applied, the heart stops immediately; when the

current is broken, the ventricles start to beat rapidly and strongly, and the arterial pressure rises. Most authors have been unable to find lesions of the heart.

Pathologic changes in the blood have been reported. Hemoglobinuria after electrocution is rather common. Alternating currents are said to hasten and continuous currents to delay coagulation of the blood. Immediately after the accident there is a leukocytosis and the appearance in the circulating blood of abnormally large white cells.

The frequent occurrence of albumin in the urine after accidents due to electricity suggests an alteration of the kidneys. This change is not due directly to the trauma but to the toxic products of abnormal protein cleavage.

A nerve through which an electric current has passed loses its irritability and conductivity. A twisting and swelling of the axons and a breaking down of the nerve sheaths have been found.

After exposure to a circuit at 600 volts or over, animals tend to show a number of signs that indicate a grave involvement of the central nervous system. This is more marked in small animals than in large animals since, other things being equal, the current density will be greater in the smaller animal. These signs consist in such phenomena as arrest of respiration and its resumption in an irregular manner, clonic spasms, loss of sensation and reflexes, great prostration and slow recovery.

Jaeger states that the effect of an electric shock is similar to a concussion of the brain; its severity and duration vary within wide limits. If the victim is not killed or rendered lifeless by the current, consciousness may return after a few seconds. On the other hand, the shock may last for hours or even for days. The unconsciousness may pass into a deep comatose condition which is interrupted by severe convulsions terminating in death.

Jellinek believes that there is a rise in the pressure of the cerebrospinal fluid following the electric shock. He recommends a spinal puncture in severe cases. Muller found blood in the cerebrospinal fluid after a shock at 30,000 volts.

Investigators do not agree concerning the changes produced in the nervous system. Many believe that visible lesions are present only when large quantities of electricity pass through the body for a long time. Small perivascular hemorrhages have been reported especially in the medulla and in the floor of the fourth ventricle; these hemorrhages are common after legal electrocution. Chromatolysis of the ganglion cells and rupture of the cells with dislocation of the nuclei have been seen. Gubler described a loosening of the glia, vacuolation of the nerve cells, and an approximation of the nuclei to the walls of the cell. Kawamura says that some nerve cells appear normal while others are shrunken and hyaline. In the medulla oblongata the Nissl substance is broken into small granules.

Mott and Schuster described the lesions in a man who recovered from a shock at a 20,000-volt potential and lived for seven hours thereafter. The autopsy was performed thirty-nine hours after death. There were petechial hemorrhages in the visceral pericardium and the urine in the blad-

der was deeply blood stained. There was a hemorrhage in the occipital lobe of the brain. The large motor cells of the central nervous system stained a diffuse dull purple. A diffuse chromatolysis exposed an intracellular and intranuclear network; the chromatin that remained was more or less encrusted on the trabeculae of this network.

Spitzka and Radasch sectioned the brains of five electrocuted criminals and found peculiar areas from 25 to 200 microns in diameter around small blood vessels. There was a central rarefied zone and a peripheral condensed one. They explained their observations on the basis of a sudden liberation of gas bubbles by the electrolytic action of the currents. Since the currents used were alternating, it is more likely that the vacuolation resulted from excessive temperatures. In electrocution the brain becomes exceedingly warm; a temperature of 145°F. has been recorded.

Although the changes seen in the central nervous system are not typical of death due to electricity, many consider them a direct result of the action of the current. Others call them artifacts or postmortem changes.

Late changes are found in the eye, with progressive diminution of vision. There are numerous flaky opacities near the anterior capsule and in the deeper layers of the lens.

In a majority of the cases that survive the immediate effects of the shock, no lasting disturbances are present. The question regarding the cause of death due to electricity centers around a paralysis of the heart or of the respiratory center. The postmortem observations do not prove any of the theories that have been advanced to explain death in fatal cases.

It is believed that men aware of the danger may withstand an electric shock which would be fatal if the current entered the body unexpectedly. The resistance to electric currents is increased during sleep. A considerable number of persons killed by electric currents reveal preexistent anatomic lesions. It is said that rabbits anesthetized with chloroform withstand a shock which would be fatal to normal animals. Fatigued animals present a greater probability of being seriously injured by the current than do nonfatigued animals. Young animals are thought to be more resistant than those which are mature.

At high voltages the brain and spinal cord are more often injured, while at lower voltages the heart is made to fibrillate. Artificial respiration by the Schäfer method is recommended as the only type of treatment holding out any hope. This procedure is primarily advantageous in the cases of respiratory failure; its value is doubtful in cases of ventricular fibrillation although here the method offers a gentle massage of the cardiac musculature. It is not known that the hearts of the larger mammals, including man, ever recover spontaneously from ventricular fibrillation. Some type of counter shock has been suggested as a means of restoring the normal rhythm of the ventricles. Thus, contact with a high voltage circuit may combat the fibrillation produced by a current at a low voltage, or stimulation of sensory nerves may accomplish the same results. Experimental studies have yielded little proof of the value of counter shock as a means of resuscitation.

At the present time chief reliance must be placed on safety appliances

and preventive regulations to reduce electric accidents to a minimum. When accidents do occur, artificial respiration should be applied at once. Boruttau (1918) found that 90 per cent. of the fatalities were due to ventricular fibrillation (3, p. 141). Ram (1922) thinks that, provided proper treatment by artificial respiration is applied, the risks to life are decidedly less with relatively high voltages than with lower ones (3, p. 141). There is a suggestion that electric companies should attempt to employ a rather phlegmatic type of individual with a stable autonomic nervous system.

Experimental Study

Introduction

The possible causes of human deaths due to electric shocks may be divided into four groups. The prolonged tetanus during the passage of the current may produce death by asphyxiation. Many fatal accidents are attributed to primary heart failure, usually with ventricular fibrillation. A third group is caused by failure of respiration through nervous inhibition or actual damage to the central nervous system. Finally, delayed death may be due to burns or other complications. The present experiments are concerned primarily with the injuries that result from damage to the nervous system. The first two possible causes of death are largely ruled out of consideration by the terms of the experiments. The application of the current was of such short duration that death due to prolonged tetanus was not likely to occur. Moreover, in small animals such as the rat, the heart recovers spontaneously from fibrillation. It seems likely that no deaths in this present series may be attributed to cardiac failure.

In planning the experiments, two questions were of primary consideration. Is it possible to demonstrate definite lesions of the central nervous system in all cases of death by electricity with respiratory failure? How many cases of delayed death are due to demonstrable lesions in the central nervous system? It must be constantly borne in mind that the findings in one species of mammals cannot be expected to apply in their entirety to other mammals including man. There is a possibility, however, that these experiments may suggest lines of investigation that may be profitably followed in the case of larger mammals whose reactions to electric shocks are more closely akin to human reactions.

There are two avenues of approach to the problem of injuries produced by electricity—experiments on animals and studies of human accidents. Animals are somewhat unsatisfactory in that they differ in their reactions to electric currents, as has already been explained. The fact that the hearts of rabbits and of rats recover spontaneously from fibrillation makes them more resistant.

In the present study, portions of the central nervous system of two men were obtained for study and sections were stained with thionin. A further description of these brains will be given later. One died from accidental contact with a 2,200-volt system, the other was legally electrocuted. In similar human material, hemorrhages and injuries of the nerve cells have already been described and these findings were to some extent confirmed in

the present studies. These abnormalities are so subtle that it would be difficult ever to prove conclusively that they were not due to postmortem changes, faulty fixation, or staining. The interesting case of Mott and Schuster already described, in which the patient lived for seven hours, is subject to similar criticism in that the autopsy was so long delayed. It seemed logical to believe that any injury to the nerve cell could be seen with particular clarity if an experimental animal was allowed to live for a period of hours or days after the electric injury, and was then killed and the central nervous system was fixed immediately. The results obtained seem to confirm this opinion.

Rats were chosen as experimental animals because of the ease with which they could be transported in numbers from one laboratory to another. They have a great advantage, as has been already mentioned, in that the heart recovers spontaneously from fibrillation.

Urquhart (3) has recently reported an elaborate experimental study of electric shocks. In one group of rabbits, the current was applied through electrodes attached to one hind leg and upon the shaved occiput. In nine of the thirty-three cases, spontaneous respiration occurred following the application of the current. In six others, artificial respiration brought about recovery. The remaining eighteen animals died. In fourteen of these it seemed likely that the heart, quite apart from fibrillation, had been damaged in some way by the current, since it stopped beating either within one minute of the application of the electric current or at a later interval in spite of continued artificial respiration.

Urquhart then allowed the current to pass through the head without subjecting the heart to the direct action of the current. One electrode consisted of a straight piece of copper wire which was inserted well back in the nasal cavity. The second electrode was arranged to fit snugly on the exposed atlanto-occipital ligament. The animals were anesthetized. In a series of experiments with currents of from 500 to 2,300 milliamperes for two seconds, all the rabbits could be saved with artificial respiration with the exception of those in which the brain stem was actually charred by burning in the region of the atlanto-occipital ligament. This occurred when the current density became too great for the electrode placed in this region. In general, a current of from 600 to 700 milliamperes produced a permanent apnea unless artificial respiration was applied. The depression of the respiratory center was more prolonged in cases in which the initiation of artificial respiration was delayed for seconds or for minutes.

The effects of the electric shock upon blood pressure as demonstrated by Urquhart are particularly important for an understanding of the present results. During the passage of the current the rabbit was in a general tonic convulsion and the heart was stopped. When the current was broken, complete muscular relaxation followed, and the blood pressure fell momentarily and then rose to about twice its normal height. The blood pressure soon fell to about one-half the normal level and then returned gradually to the normal pressure. The

explanation of this phenomenon is as follows. During the passage of the current, with more or less complete inhibition of the heart, the venous side of the circulation became greatly distended with blood, this condition resulting from the generalized tonic contraction of all the muscles of the body. The sudden cessation of this tonic spasm, when the current was broken, momentarily reduced the pressure on the arterial side and the blood pressure fell. The rapid increase in blood pressure occurred because the blood which had accumulated upon the venous side was suddenly forced into the arterial circulation. This rapid increase in blood pressure was the probable cause of many of the capillary hemorrhages which were found in the brain and the spinal cord.

Since the heart of the rat is so resistant to the effects of the electric current, no attempt was made in the present experiments to apply the current particularly to the central nervous system, leaving the heart outside of the direct path of the current. The results give the impression that the heart was not primarily damaged since it beat in every case for a short time after the respirations ceased.

Sections of the nervous system were cut and examined by Urquhart, but no definite report of this material is given. Since he believed that the nerve block was temporary, he did not expect that any typical lesions would be found. He points out that short periods of asphyxia produce changes in the structure of both sensory and motor nerve cells, those of the cerebellum and cerebrum being the most sensitive, and that therefore one must take great care in the interpretation of similar changes before attributing them to the action of the electric current. It does not seem possible, however, that the mere paralysis of respiration produced by application of a current for a few seconds up to half a minute would produce structural changes in the cells of the central nervous system.

Urquhart gave more attention to the presence of capillary hemorrhages in the nervous system since there has been a suggestion that hemorrhages were associated with failure of the cardiac and the respiratory centers of the medulla. He failed to find any evidence of this association. Although small hemorrhages were frequently found in the proximity of the dorsal motor nucleus of the vagus nerve, they were just as frequently found in other parts of the brain and the spinal cord. When these hemorrhages did occur, Urquhart believed that they were probably due to the sudden great increase in blood pressure which followed the passage of the electric current through the body and not to the local effect of the current. Their presence, he thought, was probably not an important factor in death from electricity. Since no significant morphologic changes could be noted in the brains of the animals and since he found that a majority of the animals could be saved by artificial respiration, he believed that a temporary nerve block was established in the respiratory, vagus, and vasomotor centers when the current passed directly through the brain.

J. I. H.
Feb., 1930

Methods

The 110 and 220 volt alternating and continuous current supplies were taken directly from the laboratory circuits. The 500 and 1,000 alternating current voltages were furnished by a step-up transformer with a ratio of 1:10. The frequency of the alternating current was 60 cycles. The primary voltage was obtained from a special alternator driven at constant speed and its value was controlled by adjusting the magnetic field of the alternator. The 500 and 1,000 continuous current voltages were taken from a 1,000-volt continuous voltage generator with a separately excited field. This generator was also driven at constant speed. A separate switch was used to close the circuit in which the animal was placed.

In the first experiments at 500-volt and 1,000-volt alternating current potentials, the primary voltage, feeding the step-up transformer, was furnished from a 110-volt laboratory circuit and it was controlled by means of a potentiometer type of rheostat connected across the supply mains. The amount of current taken by the animals was larger than anticipated and resulted in a considerable fall in voltage owing to the drop in the potentiometer. Measurements showed that in the 500-volt tests the voltage fell to approximately 100 volts, and that in the 1,000-volt test it fell to approximately 220 volts. The actual values varied with the size of the animals. This potentiometer type of connection was therefore abandoned and the primary voltage was controlled by means of the magnetic field. Nevertheless, the results on the circuits where the voltage was not maintained but where it fell upon the closure of the switch to about 20 per cent. of its first value were very interesting because they showed that the initial shock played a large part in the injury of the animal. With the magnetic field control, measurements were made on both the 500 and the 1,000 volt alternating and continuous current circuits which were maintained constant during each experiment.

In making the tests, the voltage was adjusted to the desired value and the electrodes were placed in position on the animal. The operator at the proper time closed the switch in the circuit in which the animal was placed. The contacts which are called instantaneous were made by manual closure and opening of the switch in the shortest possible time. Time was measured by a stop watch.

Preparatory to the shock, the rats were given ether until they were quiet. The areas where the electrodes were applied were thoroughly moistened with saline solution. A metal clip was attached at the base of the tail. The other electrode fitted snugly on the head and made a contact over the dorsal surface of the skull. After the electrodes were in place, the rat was allowed to recover from the effects of the anesthetic before the electric current was applied.

No really adequate method of artificial respiration was devised. Tracheal insufflation was not feasible in such a small animal. A respiration jar was built in which the pressure could be raised and lowered but this was of no great help. Attempts at resuscitation finally consisted in digital

pressure upon the chest, pulling out the tongue, stimulating the vagus nerves in the neck with the fingers, and efforts to keep the respiratory tract free from mucus.

Observations

The experiments to be discussed in this series were 286 in number and include groups shocked on alternating and continuous circuits at different potentials. Since the number is so large, it is necessary to present, first, statistical results obtained in the whole series; thereafter, more general findings will be considered and discussed.

The data of these experiments may be grouped and examined in a number of different ways. First, it is proposed to describe the results obtained with alternating and continuous circuits using in each case four potentials at 110, 220, 500, and 1,000 volts. It is, of course, clear that the current increased in each of these groups in rather direct ratio to the increase in potential inasmuch as the resistance remained a relatively constant factor. With each potential, characteristic results of the shock were obtained. The time that the current was allowed to flow through the body was varied in the different experiments of each series. In general, the time was longest with the lower voltages, since in all the series the duration was increased to a point where a number of the rats did not survive the shock. The different experiments will first be described in groups on the basis of the potential of the alternating and the continuous circuits and later these groups will be compared.

Alternating Circuit

110-Volt Potential.—Eleven rats were shocked with an alternating circuit at 110 volts; the current was allowed to flow for from ten to thirty seconds. The current reading in this series was from 25 to 48 milliamperes. Of these eleven rats, seven recovered, three died, and one was paralyzed. The paralysis involved the posterior portion of the body and the hind legs. On the second day following the shock, the paralyzed rat was found to be incontinent and blood appeared in the urine. Little response was obtained to nocuous stimuli applied to the posterior portion of the body.

The ten-second current application proved as fatal in this series as did the thirty-second. Of four rats subjected to the current for ten seconds, one recovered, two died, and one was paralyzed; of four that received the current for over twenty seconds, three recovered and one died immediately following the application. One of the rats that apparently recovered from the shock died three hours later.

Only one of the eleven rats breathed spontaneously following the shock; artificial respiration was used for all the others. Three of the rats did not respond to stimulation but died at once although the heart beat well for several minutes. Two of the rats that survived showed a very definite spasm of the entire striated musculature of the body, with a tremor of the extended legs, immediately following the shock. The chest was expanded and there was a spasm of the muscles of the larynx. In two, bloody fluid appeared from the nose owing to a rupture of capillaries in the mucous membrane.

Few of the animals recovered at once from the effect of the electric current. They lay quietly for several minutes to half an hour before they

attempted to walk. One animal in addition to the one showing clear-cut paralysis had a definite weakness of the hind legs following the shock; this weakness disappeared after a few hours. The animals even after they began to move about showed little activity for the first twenty-four hours. During this period they did not eat or drink. Later their behavior seemed normal.

A summary may be given of the gross appearance of the central nervous system which was removed immediately after the death of the rats. In seven the nervous system appeared grossly normal. The paralyzed rat showed a large hemorrhage in the lumbar portion of the spinal cord which will be recognized as a characteristic lesion described in detail later. One rat bled from the nose following the shock, and the hind legs were found definitely to be weak although they became normal later; in this case there was a hemorrhage in the third and the lateral ventricles. There was a developing hemorrhage in the spinal cord of one rat that died as an immediate result of the injury and in another that died three hours after exposure to the current.

In summary, it is clear that an alternating circuit at 110 volts giving a current of 25 to 48 milliamperes, allowed to flow for from ten to thirty seconds, produces severe injuries in rats. Three of eleven rats died at once, one died after three hours, and one was paralyzed. Artificial respiration had to be used in almost every case. In four rats definite gross abnormalities were found in the central nervous system.

220-Volt Potential.—The series became progressively more interesting with the higher potentials, inasmuch as the resulting abnormalities were more numerous and pronounced. Thus, of twenty-nine rats subjected to an alternating 220-volt circuit, only eight recovered without obvious defect, eleven died at once, and ten were paralyzed. The initial current readings were from 80 to 210 milliamperes. The time of current application was from five to thirty-five seconds. During the passage of the current the resistance rapidly decreased provided no burning occurred at the site of the contacts, and the current increased on long time applications, for example from 210 to 286 milliamperes.

Within certain time limits, from five to fourteen seconds, there was a slow increase in the death rate following the injury. Of four rats which received the current for five seconds two recovered completely and two were paralyzed. Six rats received the shock for fourteen seconds; four died at once and two recovered. Fourteen seconds is probably close to the upper limit of time that rats can be subjected to a circuit at this potential and any recoveries be expected. Artificial respiration had to be used for a long time to save these rats.

Two rats that received the current for five seconds began to breathe spontaneously; in all the other experiments artificial respiration had to be used. It was possible to tell almost immediately after artificial respiration was begun whether or not it would be possible to save the rat. If the chest expanded well and it was possible to force air into the lungs, the resumption of breathing was to be expected. If the chest was completely collapsed and no response was obtained, no hope of recovery could be entertained.

The experiments with alternating current differed markedly from those with continuous current, since with alternating current a spasm of the musculature persisted for several seconds or several minutes after the shock. Often a definite tremor of the extremities was seen, together with rhythmic movements of the muscles of mastication quite unassociated with any attempts at breathing. The chest was usually fixed in expansion and a spasm of the muscles of the larynx occurred so that it was difficult to expel the air from the lungs. With continuous current this persistent spasm of the musculature after the shock was seldom encountered. The expansion of the chest in the rats shocked with the alternating circuit favored attempts at artificial respiration. On the other hand, the persistent spasm of the laryngeal muscles made it difficult for air to enter.

Only four of the eleven animals that died soon after the shock failed to respond to artificial respiration. The remainder began breathing but respiration was shallow and labored and ceased after a time. One of the four was subjected to the current for thirty-five seconds. The current increased from 80 to 166 milliamperes and the rectal temperature rose from 36.5°C. to 38°C. The heart did not beat following the shock and the rat never breathed. The heart beat well for several minutes in all the other rats that died as an immediate sequel to the experiment.

The rats that survived showed many curious abnormalities as the immediate result of the injury. In many cases bloody fluid emerged from the nose and blood was seen in the eyes as the result of rupture of blood vessels in the conjunctivae. When the eye bled, the pupil on the side of the bleeding was constricted. This constriction was maintained for only a few hours.

When respirations began, following artificial stimulation, they were often definitely abnormal for a period of several hours. In many the respirations were shallow and slow, in others labored and irregular. Many breathed fast and the respirations were shallow. While a great majority breathed normally after a few hours, in others respiration was fast and shallow until they were killed several days later.

Emission occurred in one male during the application of the current. This was more common with the circuits at higher potential.

There were gross pathologic changes in the central nervous system in many rats in this series. The rats with the posterior portion of the body paralyzed following the experiment, ten in number, or 34 per cent. of the twenty-nine rats, all showed one characteristic lesion. In each of these rats an extensive hemorrhage had occurred, beginning in the lower thoracic region of the cord and extending in both directions, producing a severe necrosis of both the gray and the white matter. In this group of animals, complete transverse necrosis seldom occurred and it was possible to obtain during life some response to nocuous stimuli applied to the posterior portion of the body. These animals were not noticed to be incontinent during the first twenty-four hours following the injury but later blood was found in the urine. At autopsy the bladder

was greatly distended. Hemorrhages had occurred in the wall and often a large clot filled the bladder.

No characteristic gross pathologic lesion was found in the central nervous systems of the eleven rats that died as an immediate result of the shock. In seven the nervous system seemed normal; a beginning hemorrhage in the lumbar cord was found in three, and in one a large quantity of blood was found in the cerebral ventricles.

Of the eight normal rats, or 28 per cent. of the twenty-nine subjected to this experiment, the brain was grossly normal in six, one had a questionable hemorrhage in the lumbar cord, and no specimen was obtained from the other animal.

In summary, considerable injury was produced in a group of twenty-nine rats subjected to an alternating circuit at 220-volt potential for from five to thirty-five seconds. The initial current reading was from 80 to 210 milliamperes. Eleven rats died at once, ten were permanently paralyzed, and only eight appeared normal thereafter. Artificial respiration was used in almost every case and when breathing was resumed it was definitely abnormal. There was bloody fluid from the nose and a rupture of small vessels in the conjunctiva. Characteristic gross lesions were found in the central nervous system at autopsy.

500-Volt Potential.—Twenty-six rats were shocked with a circuit at 500-volt potential; the contact was maintained for from one to four seconds. The current readings were 240 to 490 milliamperes. Ten of these rats, or 38 per cent., recovered and were normal; thirteen, or 50 per cent., were paralyzed; and three, or 12 per cent., died immediately. It will be observed that the time the contact was maintained was relatively short in comparison with the series just studied, where the shortest time the current was allowed to pass was five seconds. Because of this variation of time element, no direct comparison of the mortality can be made. The importance of the time element will be clear from the following statements. Six rats were subjected to the current for one second; four recovered completely and two were paralyzed. On the other hand, five rats were exposed to the current for four seconds; one died at once and the other four were paralyzed. It is clear that few if any complete recoveries could be expected after a four-second contact with a system of this potential. Artificial respiration was used with all but three of the rats; when the time of exposure was relatively long, it was more difficult to initiate normal respiration.

During the time of passage of the current a strong tonic contraction of the musculature was present. The forelegs were stiffly extended and the hind legs adducted. The increased tonus persisted for several seconds after the circuit was broken; tremors and clonic movements appeared in the extremities. The chest was fixed in expansion and increased tonus of the laryngeal muscles made it difficult to expel air from the lungs or for any air to enter. Emission occurred almost invariably in the male rats subjected to the current for three or four seconds but was not seen with the shorter exposures. In one rat a vertical nystagmus of the eyes persisted for two hours following the injury. There was bleeding from the mucous membranes

of the nose and from the conjunctivae in many cases. The sex of the rats was noted in every case and no differences in susceptibility to the current were noted in the males and the females.

The gross pathologic picture differed from that already described only in the increased local injury in the areas where the contacts were applied. The typical hemorrhage in the lumbar cord was observed in those rats that were paralyzed following the injury. The central nervous systems of the rats that seemed to recover completely from the shock appeared grossly normal in every case. The surface of the cortex was badly burned in one of the animals that died immediately; one showed a hemorrhage in the spinal cord; the third was normal. In those subjected to the current for the longer periods, definite injuries were often observed at the places where the current entered and left the body. Edema of the fascia over the surface of the skull was observed in two, and in two edema of the tail was present. The periosteum over the surface at the skull was necrotic in one case; in another the injury was greater and the surface of the cerebral cortex was seared.

In summary, twenty-six rats were shocked from a circuit at 500-volt potential with a current from 240 to 490 milliamperes for from one to four seconds. Three of the animals died at once, ten recovered, and thirteen were paralyzed. No rat was normal following the four-second application. Artificial respiration was used in almost every case. Increased tonus of the musculature persisted after the shock. Bleeding from the mucous membranes occurred. Pathologic changes were demonstrated in the areas where the electrodes were applied.

1,000-Volt Potential.—Twenty-eight rats were exposed to an alternating circuit at 1,000-volt potential; only one received the current for four seconds and the remainder were shocked for from one to three seconds. The current readings were from 700 to 1,200 milliamperes. The shock with this current produced great injury not only at the points where the electrodes were placed but also in the central nervous system. Of the twenty-eight rats, nine, or 32 per cent., died at once; eleven, or 39 per cent., were paralyzed; and eight, or 29 per cent., were normal. Two of the seven rats exposed to the current for one second recovered completely, four were paralyzed, and one died. Of ten that were shocked for three seconds, three recovered, two were paralyzed, and five died as an immediate result of the injury. The single rat subjected to the current for four seconds never breathed although the heart beat and artificial respiration was continued for a considerable time.

Artificial respiration had to be used in all but three of the experiments, and considerable time elapsed, often ten minutes, before breathing was well established. Several of those that died following the shock began to breathe with artificial aid but were not able to maintain respiration. The persistence of tonic contraction of the musculature following the shock was always observed in this group. Rhythmic contractions of the muscles of mastication and of the muscles of the extremities were often noted. There

was bleeding from ruptured capillaries in the mucous membranes of the nose and from the conjunctivae. In all the males emission occurred during the shock; this is attributed to the powerful contraction of the musculature.

The heart beat regularly and powerfully in every case and death appeared to be due to respiratory paralysis. When breathing was established, it was labored for several hours; often it was irregular.

The rats that were paralyzed were very inactive during the remainder of their lives. They refused to eat and could be kept alive for only three or four days. After twenty-four hours they became incontinent and blood appeared in the urine. Nocuous stimuli applied to the posterior portion of the body elicited little if any response. They remained quiet in one position until they were moved. When disturbed, the anterior portion of the body seemed alert and active. At autopsy the characteristic hemorrhage was found in the spinal cord and the bladder was distended with blood clot.

Of the nine animals that died as an immediate result of the shock, the central nervous system appeared grossly normal in two. One showed a hemorrhage in the brain ventricles; two, a hemorrhage in the spinal cord. The surface of the cortex was badly burned in four; in one of these, small holes could be seen just beneath the surface of the cortex.

No specimen of the central nervous system was obtained from two of the rats that recovered from the shock. In two others there was a small hemorrhage in the spinal cord which did not produce sufficient damage to cause paralysis. The surface of the cerebral cortex was severely damaged in one; in another there was an abscess in the forebrain. It is important to observe that in those preparations with a hemorrhage in the spinal cord, the entire cord was soft when the rat was killed several days thereafter, and the brain stem also was very gelatinous. In the animals that showed no gross hemorrhage, the central nervous system was of much firmer consistency.

The injury produced at the site of the electrodes was extreme in the rats of this series. In those that died at once, a searing of the cortex was found. An ulcer of the epidermis on the surface of the skull was observed in two; in the remainder an edema of the subcutaneous tissue was marked. Necrosis of the periosteum indicated burning at the site of the injury, and in some cases the surface of the cortex was a sloughing mass. Comparable changes were produced near the tail electrode, with burning at the site of contact, thrombosis of the arteries, edema of the distal portion of the tail, or complete loss of the tail.

In addition to the hemorrhages in the central nervous system and bladder, extravasation of blood into the back muscles occurred in some of these rats. In one of the animals the hemorrhage in the cord was of unusual pattern, involving the gray matter of the cervical cord. It has already been explained that in certain of the preparations a hemorrhage into the substance of the spinal cord did not produce sufficient damage to cause a paralysis. Some of the paralyzed rats of this group were killed on the day of the shock. These animals were not

incontinent and no blood was found in the bladder. It is clear that the incontinence and hemorrhage are an indirect result of the shock and are sequelae of the spinal cord injury.

In summary, twenty-eight rats were subjected to a circuit at 1,000-volt potential and received a current of from 700 to 1,200 milliamperes for from one to four seconds. Nine died at once, eleven were paralyzed, and eight recovered. In addition to the lesions in the central nervous system that have been previously described, severe damage occurred at the local site of the electrodes.

500-Volt Potential with Voltage Not Maintained.—Two other groups of rats are to be considered which were injured with shocks at 500-volt and 1,000-volt potential but with the voltage not maintained. In these cases the initial shock was of the indicated potential which then fell to approximately 20 per cent. of its initial value in less than one-hundredth of a second. The current in like manner dropped at once to a level that will be indicated. These experiments belong to the early period of the work and were, in a sense, an accident. They are included here because it is felt that very definite information may be obtained from them. They indicate the importance of the initial shock in producing severe injuries, and help to explain the vascular accidents that were so frequent in the spinal cord.

Sixteen rats were shocked from a circuit of nonmaintained voltage at 500 volts for a period from quick closure and opening of the switch to fourteen seconds. The current readings were from 20 to 30 milliamperes; less than those obtained with an alternating circuit at 110 volts. Eleven of these animals, or 69 per cent., recovered completely; five, or 31 per cent., were paralyzed; and none died as an immediate result of the shock. Artificial respiration was resorted to in almost every case, and respirations were difficult and labored in almost all these preparations for a period of hours. The hind legs of one rat were weak immediately after the injury but later were used normally. A hemorrhage was found at autopsy in the cerebral ventricles. The paralyzed rats all showed the typical lesions in the cord that have been described. Paralysis was as common after short exposures to the circuit as it was after exposures for several seconds.

1,000-Volt Potential with Voltage Not Maintained.—A large group of fifty-two rats were subjected, at the time this experimental work was begun, to an alternating 1,000-volt circuit with a voltage drop following immediately upon the initial shock. The time of shock varied in this group from the time required to close and open the switch to six seconds. The current readings were from 100 to 130 milliamperes. These values were similar to those obtained from a circuit of 220-volt potential and indicate the great drop in potential. Twelve rats, or 23 per cent., recovered completely; sixteen, or 31 per cent., were paralyzed; and twenty-four, or 46 per cent., died as an immediate result of the injury. It is important to notice that although the potential and current fell in less than one one-hundredth of a second, a large number of preparations were seriously injured. The number of abnormalities was almost as great in those shocked

for shorter periods but no rats survived the exposure for six seconds.

In connection with these experiments, the question arose as to whether the position of the electrodes was responsible for the large number of hemorrhages in the lower portion of the spinal cord with resultant paralysis of the posterior portion of the body. It seemed possible that the density of current would be great in this region close to the electrode attached to the tail. Accordingly, the position of the electrodes was changed in a number of experiments.

In six rats the electrodes were applied to the top of the head and to one foreleg. Three of these rats recovered completely, one died, and two showed the typical paralysis produced by hemorrhage in the lumbar cord. In another group of six rats the electrodes were attached to one foreleg and the opposite hind leg. One of these rats died, four recovered completely, and one was paralyzed. It is important to increase the number of these experiments, but from these few it seems rather clear that the position of the electrodes is not responsible for the hemorrhages in the spinal cord.

The animals that were paralyzed all showed the gross picture of hemorrhage in the spinal cord. Hemorrhages in the cord and in the cerebral ventricles were found in a large number of the animals that died soon after the shock.

Continuous Circuit

110-Volt Potential.—Thirty-three rats belong in this group. The current of from 28 to 47 milliamperes was allowed to flow for from five to sixty seconds. About half the rats breathed spontaneously after the shock; artificial respiration was used in the case of the remainder. Twenty-eight of the rats, or 85 per cent., recovered completely; four, or 12 per cent., died; and one was paralyzed. As the experiments with continuous current are reviewed, it will be clear that few of the rats showed the paralysis so typical of the former group exposed to alternating current. In the few that were paralyzed, it was impossible to demonstrate grossly any abnormality in the spinal cord. In several of the rats, the hind legs were weak for hours after the shock but thereafter were used as well as ever.

The heart beat well after the shock in all the rats that died, and death was due in each case to respiratory failure. Almost no gross lesions were found in the central nervous system of the rats after death. When the current was allowed to flow for several seconds, it steadily increased, for example, from 40 to 53 milliamperes, provided there was no burning at the site of the electrodes. This increase in current of course implies decreased resistance on the part of the rat.

The most interesting and distinctive information concerning these experiments was obtained from observation of the animals during the passage of the current. Continuous, strong, tetanic contraction of the musculature which was always observed in injuries with the alternating current was not found here. Instead, clonic contractions of the entire body musculature began as soon as the circuit was closed. These clonic movements became more prominent if the shock was continued, and it almost seemed that the animal received some air in the

thorax. If the contact continued for over twenty seconds, spontaneous deep respirations occurred at frequent intervals and the general uncoordinated clonic movements were less marked. After forty minutes' application, the respirations and clonic movements became weak and practically ceased. The heart still beat but it was difficult to induce breathing in rats that had been subjected to the current for over forty seconds. If the rat was breathing spontaneously during the application of the current, the respirations always stopped when the circuit was broken, and artificial respiration had to be used. Breathing was often markedly abnormal for a period of hours following the shock.

These experiments with a circuit at low potential permit a considerable variation in the period of application without great damage to the animal and give an opportunity for further analysis of the time element. With application of the current for less than twenty seconds all the rats breathed spontaneously when the switch was opened, and no artificial respiration was required. The four died after exposure for twenty, forty-five, fifty, and sixty seconds, respectively.

In summary, clonic rather than tetanic contractions of the musculature occurred during shocks with a continuous circuit at 110-volt potential. Few of the rats were seriously injured. If the shock continued for over twenty seconds, spontaneous respirations occurred but these stopped when the circuit was opened, and artificial respiration had to be used. After longer exposures to the current (forty seconds), spontaneous respirations and clonic movements of the musculature gradually ceased. Few gross lesions were found in the central nervous system.

220-Volt Potential.—Nineteen rats were subjected to a continuous circuit at 220-volt potential; the current was 100 to 250 milliamperes. The current was allowed to flow for from five to thirty seconds. When the contact was maintained and no burning occurred at the site of the electrodes, the current gradually rose, for example, from 155 to 194 milliamperes. Ten, or 53 per cent., of the rats recovered; eight, or 42 per cent., died; and one was paralyzed. The time of application in this series was rather long; only one out of three survived the application for thirty seconds. Six rats received a shock for five to ten seconds; none of them died, but one was paralyzed. Several of the animals that received the current for over twenty seconds breathed spontaneously during the last part of this period, but respirations always ceased when the shock ended. Artificial respiration was used on most of the rats shocked for over five seconds. Few gross changes were found at autopsy. No hemorrhage could be demonstrated in the spinal cord of the paralyzed rat.

Clonic contractions of the musculature during the shock occurred in all these animals. When the application was over, the clonic movements sometimes persisted for a few seconds but no generalized contraction was present. For this reason artificial respiration was, in general, more satisfactory with this group than with those shocked from an alternating circuit of similar potential. A few of the rats breathed spontaneously following the shock and then stopped, nor could further res-

piration be induced. The heart beat well in all the animals that refused to breathe following the injury. Many of those that recovered breathed poorly for minutes or for hours.

500-Volt Potential.—Thirty-seven rats were shocked with a continuous circuit at 500-volt potential, the application lasting for from one to four seconds. The current readings were 280 to 640 milliamperes. Of this total group of rats eighteen, or 49 per cent., recovered completely; seventeen, or 46 per cent., died at once; and two, or 5 per cent., were paralyzed. Clonic contractions of the skeletal musculature occurred during the application of the current and often persisted for several minutes thereafter. Even in those animals which refused to breathe following the shock, the heart beat strongly and well. Respirations were markedly disturbed for several minutes.

Only two of this series of rats were paralyzed; in several others the hind legs remained weak for twenty-four hours but were used normally thereafter. No signs of gross hemorrhage in the cord were found even in the rats that were permanently paralyzed. In a number of these rats, bloody fluid came from the nose and sometimes from the mouth immediately following the shock. Small vessels in the conjunctivae often ruptured and blood emerged from the eye slit.

The continuous current produced less stimulation of the autonomic system than did the alternating current, if this can be judged by the effect upon the pilomotor system. The fur was definitely roughened and stood out from the body immediately after shock with the alternating current; with the continuous current the coat of fur lay smooth.

This group of experiments with the continuous circuit at 500 volts was the only series in which a tendency to convulsions was noticed. Four rats exhibited typical clonic convulsive seizures some five or ten minutes after the shock. These convulsive attacks occurred spontaneously or upon touching the rats, which appeared to be definitely hyperirritable. They never continued longer than an hour and the animals were perfectly normal thereafter. No gross lesions were demonstrable in the central nervous system. Observation of these seizures gave the impression that the vestibular mechanism was irritated.

This group of experiments gave a further opportunity for a consideration of the size of the animals as a factor in the injury produced by electricity. The first experiments were performed upon twenty-five rats which were small, young adults born some three months before. When the total experiments were completed, it was felt that this series perhaps could not be compared with the rest and the results were checked with a group of twelve large rats of unknown age. This check indicated that with the current flowing for the same time, less injury occurred in the larger rats. The amount of injury produced in small rats with a three-second exposure to the current could be achieved with the large rats after a four-second exposure. Of eleven small rats shocked for two seconds, seven died and four were normal. Four large rats recovered completely under the same conditions. Of seven small rats shocked for three seconds, six died and one was par-

alyzed. Four large rats under the same conditions showed two deaths and two recoveries. With a four-second exposure, two large rats died, one recovered, and one was paralyzed.

There was some indication in these animals of local damage at the site of the electrodes. Edema of the subcutaneous tissues over the skull was often observed at autopsy.

In summary, rather characteristic abnormalities were observed after exposure to a continuous circuit at 500-volt potential. Four of the rats showed a tendency to convulsions during the immediate period of recovery from the shock. No disturbance of pilomotor innervation was seen comparable to that following injuries with alternating current. Large rats are more resistant to the current than are smaller ones. Small hemorrhages from mucous membranes occurred during the shock. Few rats were permanently paralyzed and no spinal cord hemorrhages were found at autopsy.

1,000-Volt Potential.—Thirty-three rats were subjected to a continuous current at 1,000-volt potential for periods varying from simple closure of the switch to four seconds. No animals survived a contact of one second or over. For the purpose of study, a contact of one-half second was approximated as closely as possible. The current readings were from 600 to 1,100 milliamperes. Severe abnormalities were produced by these contacts but practically no gross changes were found in the central nervous system after death. Twenty of the thirty-three rats, or 61 per cent., died at once; nine, or 27 per cent., recovered; and four, or 12 per cent., were paralyzed. These findings need further explanation. Thus, eight received the current for the time required to close and open the switch. Of these eight animals five recovered, two died, and one was paralyzed. Thirteen were shocked for approximately one-half second; four were normal, three were paralyzed, and six died at once. No rats survived an application of the current for one second or over. Since the first twenty-six experiments employed small adult rats about three months old, the findings were checked with a group of large adult animals. These proved to be no more resistant to the shock than were the smaller animals.

Clonic contractions of the musculature were observed in these rats during the shock that persisted after the circuit was broken. There was no tetanic contraction of the musculature following the shock and in most cases the chest was collapsed. In many of the experiments there was no response to artificial respiration and no air entered the collapsed chest although the heart beat well for one or two minutes. In the group shocked for one second or over, no response to artificial respiration was ever obtained.

Bleeding from the mucous membranes of the nose and from the conjunctivae occurred in several of the group. One rat was extremely hyperirritable to all stimuli immediately following the shock.

Four of the rats were paralyzed. Two of them became incontinent on the second day although no blood was ever present in the urine. The legs became stronger in one of these preparations and by the fourth day were used fairly well. Nocuous stimuli applied to the posterior portion of the

body elicited a response in all these rats. No gross injury in the spinal cord was found at autopsy.

The most distinctive abnormality found only in this group was priapism which occurred in practically all the males which survived and in four cases continued until the rats were killed, six days after the shock.

Considerable local damage occurred around the electrodes. This consisted in edema of the subcutaneous tissue over the skull and a dry necrosis of the tail in three of the rats.

In summary, no rats survived contact with a continuous circuit at 1,000 volts for one second or over. The rats that received the current for fractions of a second were seriously damaged. The characteristic abnormality of this particular group was persistent priapism in the male. Considerable local damage occurred at the site of the electrodes. Little gross injury could be observed in the central nervous system.

Comparison of Abnormalities Produced by Alternating and Continuous Circuits

110-Volt Potential.—In many ways the series of rats subjected to alternating and continuous circuits at the same potentials do not yield to exact comparison. The number of animals varies in the different groups and the time element shows discrepancies, since in each group the time was increased until very definite abnormalities were produced. In order to equalize varying numbers of experiments, the results will be expressed in percentages. The greatest abnormalities would be expected, all other things being equal, in the group that was subjected to the current for the longer periods of time. Sixty-four per cent. of the rats shocked with the alternating circuit at 110 volts recovered completely, 27 per cent. died, and 9 per cent. were paralyzed. With the continuous current, 85 per cent. recovered completely, 12 per cent. died, and 3 per cent. were paralyzed. The continuous current group received longer shocks than did the alternating. If the rats that were paralyzed and those that died at once are grouped together, 36 per cent. of the alternating current series showed abnormalities, in contrast with 15 per cent. in the continuous current series. It must be concluded from this consideration that an alternating circuit at 110-volt potential is somewhat more dangerous for rats than a continuous circuit. Paralysis due to injury of the spinal cord was more common with the alternating current. The current readings with the continuous circuit were somewhat higher than with the alternating.

The striated musculature of the body exhibited a tetanic contraction during the application of the alternating current. Some of the rats bled from the nose as a result of rupture of capillaries in the mucous membranes. Artificial respiration had to be used in most of the experiments. In the rat that was paralyzed, hemorrhage was found in the spinal cord.

With the continuous current, clonic contractions of the striated musculature continued throughout the shock. If the shock was continued over twenty seconds, spontaneous respirations occurred which stopped when the circuit was opened. Artificial respiration was required only during the longer periods of current application.

Few gross injuries were found in the central nervous system.

220-Volt Potential.—In this group, again, the duration of the shock was relatively longer in the continuous than in the alternating current series. The current readings compare very well. Twenty-eight per cent. of the alternating current group recovered completely, 38 per cent. died at once, and 34 per cent. were paralyzed. Of the continuous current group, 53 per cent. recovered completely, 42 per cent. died, and 5 per cent. were paralyzed. The percentages that died at once agree closely, 38 with alternating and 42 with continuous current. Paralysis was much more common in the alternating current group, 34 per cent. as compared with 5 in the continuous current group. If the rats that died at once and those that were paralyzed are grouped together, the total percentage of abnormalities following the alternating shock was 72, as compared with 47 following the continuous. Again it must be concluded that an alternating circuit at 220 volts is slightly more dangerous to rats than a continuous circuit.

In the series of rats shocked with the alternating circuit, a strong, continuous spasm of the striated musculature was observed during the period of current application. Artificial respiration was used for almost all the animals. When breathing began, it was seriously disturbed for some time. Bleeding occurred from the conjunctivae and the nose. Many of the animals at autopsy were found to have hemorrhages in the spinal cord or the cerebral ventricles.

In the continuous current group, clonic contractions of the musculature occurred during the exposure. Artificial respiration was often required and afterward breathing was fast, shallow, labored, or irregular for several minutes or for hours. There were no hemorrhages, and very little gross change was found in the central nervous system at autopsy.

500-Volt Potential.—A considerable number of rats were subjected to alternating and continuous potentials of 500 volts for from one to four seconds. The current readings in this whole series were quite comparable and averaged some 400 milliamperes. As a result of shock with the alternating current, 38 per cent. of the rats recovered completely, 12 per cent. died at once, and 50 per cent. were paralyzed. With the continuous current, 49 per cent. recovered completely, 46 per cent. died at once, and 5 per cent. were paralyzed. It may be said, therefore, that more rats died immediately as a result of contact with the continuous circuit than with the alternating circuit—46 per cent. as opposed to 12. On the other hand, more recovered completely after the continuous shock—49 per cent. as compared with 38. The discrepancy again lies, of course, in the number of rats that were paralyzed; this number was decidedly greater in the alternating current group—50 per cent. as contrasted with 5. If the total abnormalities resulting from the shock are grouped together, it is found that they include 62 per cent. of the rats in the alternating series as compared with 51 in the continuous. In summary, fewer rats survived the initial respiratory injury in the continuous current group,

whereas a great many were left with a residual paralysis in the alternating current group.

There was bleeding from rupture of small blood vessels in the nose and conjunctivae in the alternating current group. Artificial respiration was required for almost all the rats of this series. The strong tonic contraction present during the shock persisted for a few seconds thereafter. Some local injury occurred in the region where the electrodes were applied.

The continuous current group also showed some bleeding from the nose. Artificial respiration was used in almost all the experiments and often the chest was collapsed after the shock and no adequate response was obtained. The clonic contractions of the musculature persisted after the shock. This was the only group of rats that showed convulsive phenomena during the period of recovery.

1,000-Volt Potential.—Rats were subjected to alternating and continuous circuits at 1,000 volts; the current readings were quite similar in the two groups and averaged some 900 milliamperes. The time factor on the other hand showed variation in the two groups owing to the fact that no rats subjected to the continuous current survived a contact of one second or over. On the other hand, in the alternating current group a few rats survived a three-second application. There is, therefore, a great difference in the susceptibility of the rats to the continuous and the alternating circuits at 1,000-volt potential on the basis of time.

A general summary shows that with the alternating current 29 per cent. recovered completely, 32 per cent. died at once, and 39 per cent. were paralyzed. With the continuous current 27 per cent. recovered, 61 per cent. died at once, and 12 per cent. were paralyzed. The total abnormalities in the alternating current series included 71 per cent. of the rats; in the continuous current series they included 73 per cent. If the time element is taken into consideration, the inevitable conclusion is that for rats the continuous circuit at 1,000 volts is considerably more dangerous than the alternating.

With the alternating current severe injuries occurred at the site of the electrodes. Hemorrhages in the spinal cord had occurred in the rats that were found to be paralyzed. Rupture of small vessels produced hemorrhages in the mucous membrane of the nose and in the conjunctivae.

In the continuous current series severe injuries again occurred at the site of the electrodes but there was much less evidence of hemorrhages in the central nervous system and also in the mucous membranes.

Discussion of Results of Experiments

The foregoing pages give an impression of the type of data collected in these experiments and of the way in which these data were obtained. There follows a topical presentation of the information under the headings concerning which it seems possible to present a discussion.

The Animal.—The rat is a convenient animal for such experimental procedures. It has the advantage, for this particular study, that the heart recovers spontaneously from fibrillation. In such a small animal the current must flow in considerable con-

centration throughout the whole body. It must constantly be remembered that the results obtained from a study of one experimental animal cannot be directly applied to a consideration of other animals or of man. It is expected that the pathologic changes in the brain, the study of which formed the main object of this experiment, will be found to be similar in all animals.

Difficulties of Standardizing Lethal Application.—In this type of biologic experiment it is impossible to standardize the lethal application of electricity, for the number of variable factors is too great. In each of the series with either alternating or continuous circuits at one constant voltage the time element was introduced as a variable. The rats differed in size, age, and degree of health and vigor. The amount of anesthesia at the time of shock was not a constant. An attempt was made to express the amount of current and the time in milliampere-seconds, with the idea that it might be possible to correlate this factor with the abnormalities produced in the rats. This adds nothing to the clarity of the problem. It is, moreover, well known that an alternating voltage is constantly varying in magnitude and its value at the instant of closing the switch may also have some effect upon the results.

Position of Electrodes.—The electrodes, in this series of experiments, made contact at the base of the tail and upon the surface of the skull. Urquhart, in previous experiments with rabbits, tested the effect of electricity upon the nervous system by making the contact so that the current flowed only through the head and particularly through the brain. This arrangement never occurs in electric accidents. Urquhart often burned the nervous system directly. In the present experiments burning of the central nervous system was very rare and occurred only with the alternating circuit at 1,000-volt potential.

The position of the electrodes is certainly one factor in experiments of this kind that offers infinite possibilities of variation. In the course of the present study, the question arose as to whether the position of the electrode upon the tail had any part in the production of paralysis in the spinal cord. In order to test this, the electrodes were shifted in one group of rats to skull and one foreleg or to alternate fore and hind legs. The impression was gained that the position of the electrodes upon the surface of the body was not important in the production of the spinal cord hemorrhages.

Effect of Anesthetic upon Injuries Produced.—There are statements in the literature that anesthesia with chloroform diminishes the injury produced by electricity. Also men are supposed to withstand an electric shock better when asleep and when the shock is expected. In the present experiments the mortality was definitely greater with deep anesthesia than in rats that had recovered somewhat from the effects of the ether. It was the practice to administer the shock when the rats had almost completely recovered from the ether.

Comparison of Results of Injuries upon the Sexes.—The sex of the rats was noted in these experiments to learn whether injuries were more common in one sex than in the other. No sex differences were found, with the

exception of the fact that pregnant rats seldom recovered from the injury.

Age and Size of Animals.—There is a suggestion in the literature that the extremes of life are less injured by contact with electricity than are the means. A number of experiments were performed upon young adult rats born three months before. The remainder of the animals were much larger but of uncertain age. It was found that the smaller and undoubtedly the younger animals were not so resistant to the current as were the larger and older rats. This was clearer when the time element was taken into consideration. The larger and older rats could withstand a shock from a circuit at given potential longer than could the smaller and younger ones.

The Current.—No presentation of the experiments has been given on the basis of the amount of current; this is indeed impossible, for the experiments were planned in series with different potentials. The currents form a graded series that could scarcely be arranged in convincing groups. It is realized that severe criticism may be presented against this arrangement; nevertheless, it has its advantages which will be mentioned now.

Urquhart planned his experiments to keep the amount of current passing through the body constant. He suggests that the potential of the current is of little importance. However, with the electrodes attached to the head he has no adequate data concerning the actual amount of current passing through the organ to be studied when the electrodes are applied to the periphery of the body.

The amount of current passing through an animal with a constant potential and with a given position of the electrodes is a function of the contact resistance and the size of the animal. In accidents with electricity the potential is the known factor and no information can be obtained concerning the resistance or the current that flows through the body. Moreover, the power and light distribution is done at a constant potential so that the voltage is a standardized factor. The ideal arrangement, however, would be to know the actual amount of current flowing through the central nervous system.

Resistance.—The resistance is another factor in these experiments that has not been discussed. Two factors must be considered: the resistance of the animal and the resistance at the site of contact of the electrodes. Both these factors are subject to considerable variation. The total resistance showed a steady decrease as the potential of the circuit was increased. Thus, the average resistance for the series of rats with a continuous circuit was 2,685 ohms at 110 volts, 1,635 ohms at 220 volts, 1,385 ohms at 500 volts, and 1,365 ohms at 1,000 volts. Similarly, with the alternating circuit it was 3,090 ohms at 110 volts, 1,890 ohms at 220 volts, 1,425 ohms at 500 volts, and 1,140 ohms at 1,000 volts. This drop in resistance with the higher potentials is believed to be due almost exclusively to the decrease in importance of the contact resistance.

When the current was allowed to flow for several seconds, the resistance also decreased provided the electrodes were able to carry the load and no burning occurred at the site of the electrode. With this decrease in re-

sistance the current increased. When local burning occurred, the resistance did not decrease.

The exact weight of many of the rats was determined and the resistance was calculated for groups in which the potential was constant, and was compared with the weight. A definite decrease in resistance was noted as the size of the animals increased.

Voltage.—A considerable discussion has already been given of the abnormalities produced in rats with alternating and continuous circuits of known potential. The experiments have indeed been grouped on this basis. Many data have been presented and it is clear that the injuries increase as the potential is raised.

Attention may be called again to the experiments with an alternating circuit at 500 and 1,000 volt potentials in which the voltage was not maintained but fell to approximately 100 and 220 volts after the initial shock. In these rats the damage was much greater than in those injured with circuits at 110 and 220 volts. More animals were paralyzed and more died as the immediate result of the injury. It is clear that the initial shock when the circuit is closed is of great importance in determining the injury to the animal.

Comparison of Abnormalities Produced by Alternating and Continuous Currents.—Considerable space has already been devoted to a comparison of the abnormalities produced by alternating and continuous currents. It is sufficient to point out here that with circuits at 110 and 220 volts more injuries are produced in the rats with the alternating current than with the continuous current. This was also true at 500-volt potential but with a circuit at 1,000-volt potential it was clear that the continuous current produced greater injury than the alternating. This was particularly well shown when the time element was taken into consideration. The paralyses due to hemorrhages in the spinal cord were certainly found more frequently in the alternating current series. Although a few rats showed paralysis of the hind legs with the continuous current, little evidence of gross hemorrhages was found in the cord. Different types of abnormalities were found after contact with the two types of currents, and these are adequately discussed in other portions of this paper.

Certainly the experiments with rats do not confirm the hypothesis that alternating currents are four times more dangerous than continuous. They suggest that any comparison must be on the basis of a constant potential. Thus at 110 and 220 volts greater abnormalities were produced with the alternating current, at 500 volts the effects were more equalized, and at 1,000 volts the continuous circuit was more damaging than the alternating.

Duration of Contact.—One fact clearly demonstrated in these experiments that perhaps has not been sufficiently stressed in previous investigations is the importance of the duration of the contact in the injury produced in the rats. For example, no rats survived a contact with a continuous circuit at 1,000 volts for one second or over, although several survived exposure for fractions of a second.

The importance of the time element was more clearly shown after shocks with the lower voltages, since more

time variation was possible without a uniform lethal result. Thirty-three rats were subjected to a continuous circuit at 110 volts for periods varying from five to sixty seconds. One death occurred with a twenty-second exposure; three deaths occurred with exposure from forty-five to sixty seconds.

Another proof of the importance of the exposure time may be obtained from the series with a continuous circuit at 220 volts. Of six rats exposed to the current for from five to ten seconds, five recovered completely and one was paralyzed. Of nine rats exposed to the current for from fifteen to twenty seconds, six died and three recovered.

Further examination of the experiments gives the impression that the paralysis seen so often in the rats, particularly in those exposed to the alternating circuits, was dependent less on the time element than on the initial shock to the rat. The group of experiments in which the potential of the current dropped markedly after the initial contact tends to bear out this hypothesis.

Artificial Respiration.—The methods of artificial respiration that were possible in such a small animal were not the most ideal. It is hoped that these results may be checked up on a larger laboratory animal in which the lungs may be insufflated with air through a tracheal tube. A small respiration bottle was built with a rubber diaphragm fitting snugly around the rat's neck so that the head was outside the bottle and the body within. It was possible alternately to raise and lower the pressure in the jar by means of a pump. This method, again, was not very satisfactory for such a small animal. Finally digital compression of the thoracic cavity seemed the most efficient method of inducing breathing. The tongue was held out of the mouth. Some attempts were made to stimulate the vagus nerves in the neck by stroking the neck with the fingers. Mucus was removed from the throat when it threatened to obstruct the air passages.

Adequate artificial respiration is of enormous importance. Urquhart believed that with artificial respiration all the animals in which the current passed only through the head could be saved, provided no actual burning of the nervous system occurred. On this basis he proposed his theory of temporary block in the respiratory center without permanent damage.

In the present experiments the brain was actually burned in only a very few of the rats, and those after contact with circuits at 1,000 volts. The heart in practically every case beat strongly after the shock. If Urquhart's conclusions are correct, all the rats should have recovered completely provided artificial respiration was adequate.

Certainly a large number of the rats were severely incapacitated with hemorrhages in the central nervous system, particularly with the alternating circuits. A large number of the hemorrhages occurred in the cord; at least five rats died within four hours after the shock as the result of large hemorrhages in the fourth ventricle pressing on the medulla.

On the other hand, a large number of rats never breathed after the shock, but died at once. At autopsy developing hemorrhages in the central nervous system were found in many. It is the opinion of the present authors that few if any of these rats could have

been saved by any method of artificial respiration. The only way to prove this conclusively is to control these experiments with larger animals in which artificial respiration can be carried on through a tracheal tube. Sections of the central nervous system of all the rats are being prepared and it is hoped that in all cases the cause of death may be proved.

With the circuits at higher voltages artificial respiration was, in general, more successful with the alternating current than with the continuous current. With the alternating current the strong tonic contraction of the whole musculature that occurred throughout the shock persisted for several seconds after the switch was open. The chest, in each case, was fixed in maximal expansion. The spasm of the laryngeal muscles often made it difficult to expel the air or for any further air to enter, but manual manipulation of the chest often initiated spontaneous breathing. With the continuous current, on the other hand, the chest was completely collapsed at the end of the shock. The muscles were flaccid and no air could be forced into the chest.

It is important to emphasize again that artificial respiration should be initiated immediately following the shock; the slightest delay decreases the probability of recovery.

Effect of Current upon the Heart.—Mention has already been made of the fact that the heart of the rat is particularly resistant to the electric current, since it recovers spontaneously from ventricular fibrillation. It is thought that no rats in this series died as the result of cardiac failure following the shock. This makes it possible to focus the attention on the respiratory failure and its possible basis in lesions of the central nervous system.

After the shock, the heart in almost every case beat strongly and regularly. It grew gradually weaker within the first two minutes if breathing was not resumed.

Effect of Current upon Respiration.—Rats shocked on the 110-volt continuous current system breathed spontaneously during the application if it was continued over twenty seconds. During the first twenty seconds of the application quick clonic contractions of the entire striated musculature occurred and it seemed as if some air might be taken into the lungs. After longer applications normal deep respirations occurred at regular intervals. If the contact was continued for over forty seconds, the respirations and clonic movements grew feeble and finally ceased. When the contact was broken while the rat was breathing spontaneously, respirations promptly stopped and measures had to be taken to initiate them again. Spontaneous respirations during the shock were not seen with the alternating circuit at 110 volts, but the periods of application were shorter and never exceeded thirty seconds. None of the other series of rats breathed during the shock.

When the circuit was broken, breathing seldom began spontaneously and artificial respiration was used in practically every case. A large number of rats never breathed. In those in which respiration was resumed, it was in almost all cases abnormal for a period of minutes, hours, or days. In some cases it was shallow and fast, in others slow and labored with the accessory muscles of respiration brought

into play. Some breathed with a definite stridor or respiratory grunt. In other cases breathing was irregular and a definite number of from five to ten breaths would be followed by a pause. These abnormalities suggest an intense injury to the respiratory apparatus. In many cases these respiratory difficulties continued for several days, until the rats were killed. A few animals died after a few hours and a large hemorrhage was found in the fourth ventricle.

Effect of Current upon Striated Musculature.—With alternating circuits at all the potentials, a constant tetanic contraction of the striated musculature occurred throughout the period of the shock and at the higher voltages persisted for a few seconds after the circuit was opened. With the continuous currents at all potentials, clonic contractions occurred during the shock and sometimes persisted thereafter. At 110-volt potential these clonic contractions were so weak that normal respirations were able to break through if the contact was continued for over twenty seconds. It seems from these observations that with continuous currents at low potential it might be possible to break the circuit with voluntary effort. The tetanus of the muscles with the alternating current when the circuit is closed is very sudden and severe, and undoubtedly accounts for the severe soreness and pain in the muscles of humans who survive.

Following the shocks with alternating circuits at the higher potentials used, abnormal contractions of the striated musculature ensued. In many cases rhythmic movements of the muscles of mastication occurred quite unrelated to respiratory movements. Clonic contractions of the extremities occurred. One rat exhibited a vertical nystagmus that persisted for two hours. Convulsions were observed in a few animals exposed to a continuous circuit at 500 volts. Abnormal tremors and spasms of the musculature were observed in many of the rats for days following the injury.

Effect of Current upon Smooth Musculature.—After injury with the alternating current the hair of the rat was ruffled and stood out from the body; after injury with the continuous current the fur lay smooth and sleek. This suggests an irritation of the pilomotor mechanism with the alternating current that did not occur with the continuous. When rupture of blood vessels occurred in the conjunctiva the pupil was, in every case, found to be greatly constricted in contrast with the normal eye.

General Activity of Rats Following Shock.—Few of the rats were active immediately following the shock. Most of them when placed upon their backs lay quietly for periods from five minutes to over an hour. Breathing was usually grossly disturbed. When they began to attempt to walk again they were considered to have recovered. The rats that later appeared completely normal were quiet for the first twenty-four hours and refused food and water during that time. The paralyzed rats never became active, never ate, and could be kept alive for only three or four days. When the period of initial shock was unduly long, it was possible to predict that a hemorrhage had occurred in the central nervous system.

Convulsions.—Convulsions were seen

only in the series of rats exposed to a continuous circuit at 500 volts. Four animals during the first hour following the shock showed typical clonic convulsions of the body and extremities. They were all hyperirritable to stimulation, and the convulsions occurred spontaneously or could be initiated by touching the animal. They suggested an irritation of the vestibular mechanism. No gross lesions in the central nervous system were found in these rats.

Priapism and Emission.—Priapism occurred in many of the males shocked with a continuous circuit at 1,000 volts. In four rats this condition persisted for six days, until they were killed. This condition is often produced by spinal cord irritation.

Emission occurred in the males subjected to alternating circuits at 500 and 1,000 volts. It is believed that this was produced by the strong contraction of the musculature.

Hemorrhages.—Following the shock, hemorrhages were observed in different portions of the body. In numbers of the rats, particularly with the alternating currents, a small amount of bloody fluid emerged from the nose; this was produced by the rupture of small vessels in the mucous membrane. Likewise blood was found in one or both eyes as a result of rupture of vessels in the conjunctiva. When artificial respiration was begun, a rush of blood and frothy fluid came from the mouth in a few cases; it is probable that hemorrhages had occurred in the lungs. However, the methods of artificial respiration were strenuous for such delicate animals and secondary trauma may have produced some of these injuries.

The hemorrhages in the central nervous system are of the greatest interest. Often it was clear that some blood had escaped into the subarachnoid space. Microscopic studies that will be reported in greater detail later revealed small hemorrhages in the substance of the brain. These were particularly common in the brain stem. Rupture of the arteries of the choroid plexus produced the common picture of hemorrhage into the cerebral ventricles. At least four rats died during the first few hours following the shock from large collections of blood in the fourth ventricle.

The mechanism of hemorrhage in the spinal cord is very typical for all the cases, and from the microscopic material already available the story of its development can be reconstructed. The escape of blood was often due to the rupture of a small artery in the posterior septum of the spinal cord in the lower thoracic region. The blood escaped among the posterior column fibers of the cord, producing considerable damage and extending for a considerable distance in both rostral and caudal directions. If the hemorrhage remained small and limited to the posterior columns, little abnormality was produced in the behavior of the rats. In the majority of cases the blood extended ventrally till it broke into the central canal, making possible a greater spread up and down the cord. Further extension into the ventral columns pressed upon the ventral cells or produced injury of the tracts to a maximal complete transverse necrosis of the cord.

The gross pathologic picture in rats which showed severe paralysis of the posterior portions of the body was

this. On exposing the dorsal surface of the cord it was found to be abnormally soft and the lower portion was almost fluid. The posterior columns had a reddish-lavender appearance and this abnormal color occurred as far cranially as the upper thoracic region. The lower thoracic and lumbar areas of the cord were of a reddish color and of almost fluid consistency. When transverse sections of the hardened cord were cut, it was found that in the upper thoracic region only the posterior columns were necrotic. In the lower thoracic area the entire cord was often completely disintegrated.

When microscopic sections were examined it was noticed that few signs of inflammation were present in the necrotic areas. There were a small number of white cells composed of an equal number of polymorphonuclear and mononuclear cells. Many of these cells contained fat. The red blood cells were inconspicuous and the area was filled with an amorphous substance produced by the breaking up of the axons and the myelin sheaths. The central canal had been torn open and in come cases there seemed to be a slight proliferation of the ependymal cells.

In a few cases the hemorrhages in the spinal cord were of a different pattern. Blood had escaped into the gray matter of the upper thoracic cord in one case. Several specimens showed a rupture of arteries that enter the ventral portion of the cord at the point where the ventral roots emerge giving a picture of two symmetrical necrotic areas on either side of the ventral midline.

The hemorrhages were much more common as a result of shocks with alternating than with continuous currents. The time element was of little importance since they were as often found after short exposure as after long exposure to the current.

Theories may be considered that will account for the production of these hemorrhages. Urquhart has shown that there is a rise in blood pressure to twice its normal height in the period immediately following the shock, and he believed that the hemorrhages were due to this heightened blood pressure. Such a theory would account clearly for all the hemorrhages described in the rats, with the possible exception of those in the spinal cord. Much of the current passing through the body is conducted along the blood vessels and might produce a necrosis of the vessel walls with secondary hemorrhage. Secondary hemorrhages seem to play little part in the present experiments.

To return to a consideration of the hemorrhages in the spinal cord, it is worthy of note that practically all of them were produced by the rupture of small arteries entering the posteromedial septum of the spinal cord in the lower thoracic region. The uniformity of the trauma is difficult to explain on the basis of a rise in blood pressure throughout the body. The hemorrhage appeared to occur always at the place of greatest curvature of the spinal column. The duration of the shock had little influence in the production of the spinal hemorrhages. It might be suggested that the sudden strong contraction of the striated musculature and particularly of the deep back musculature when the current was first applied, exerted enough pull upon the spine and subsequently

upon the cord to produce the rupture of the arteries. This is further suggested by the fact that hemorrhages were often found in the deep back musculature. The spinal cord lies so free in the vertebral canal that it is difficult to imagine that any sudden pull on the spine, no matter how violent, could injure the blood vessels in the cord.

Paralysis.—The hind legs and the posterior portion of the body were paralyzed in a large group of rats after contact with electric circuits at different potentials. The paralysis was more common after shocks with alternating currents than after shocks with continuous currents and there were other distinguishing features of the two groups.

Weakness of the hind legs in the rats shocked with continuous currents, even though severe directly after the injury, had a tendency to decrease rapidly or even to disappear entirely. Even in those rats in which the condition persisted and incontinence developed, gross signs of hemorrhage in the spinal cord were seldom found at autopsy. The paralysis seen after injury with continuous currents must be attributed to other factors than hemorrhage. The characteristic neurologic lesions produced with the continuous circuits were convulsions, temporary paralysis, and priapism. All these may be attributed to irritation of the central nervous system.

In the case of paralysis following shocks with alternating circuits, it was possible to gauge during the life of the animal the extent of the hemorrhage. When the rats had recovered from the period of complete inactivity following the injury and attempted to walk, they dragged the hind legs. Nocuous stimuli were applied to the hind legs and tail; if no active response was obtained during the first few hours following the shock, it was concluded that the hemorrhage had been severe, involving almost the whole lower portion of the cord and completely interrupting the pathways.

The subsequent behavior of this group of paralyzed rats was characteristic. After twenty-four hours the majority of the animals were incontinent and blood was found in large quantities in the urine. None of the animals would eat or drink. They showed no spontaneous activity and lay quietly for hours at a time in any position in which they were placed. If disturbed, the anterior portion of the body was active. None of them could be kept alive for more than three or four days.

It seemed possible that the density of the current close to the contact applied to the tail might be responsible for the severity of the injury in the lower portion of the cord. Application of the electrodes to the head and one foreleg or to one foreleg and the opposite hind leg did not reduce the number of hemorrhages. It must be concluded that the paralysis of the posterior portion of the body was primarily due to hemorrhage. Although developing hemorrhages in the cord were found in a number of rats that died as an immediate result of the shock, it is doubtful whether the spinal cord injury was responsible for this immediate death. The paralyzed animals had no hope of permanent survival.

Incontinence and Hematuria.—Twenty-four hours after the shock most of the paralyzed rats were found

to be incontinent and blood was present in the urine. The incontinence and hematuria were indirect results of the spinal cord injury. The hemorrhage cut off the efferent stimuli to the bladder with resulting atony of the musculature; this subsequently became so distended that small blood vessels in the wall ruptured with escape of blood into the cavity. At autopsy the bladder was found to be greatly dilated; often a large blood clot filled the cavity. Characteristic microscopic changes were found in the bladder wall and in the kidneys, which will be described in a subsequent report.

Effect of Current upon Blood Pressure.—Hemorrhages in the present experiments were much more common with the alternating current than with the continuous current. The question arises as to whether the increase in blood pressure was as great following injuries with the continuous current. It is easily possible that with less severe tetanic contractions of the muscles during the continuous current injuries the blood pressure did not subsequently become markedly elevated. This should be studied in some larger laboratory mammal.

Effect of Current upon Temperature.—With currents at low potential, death may sometimes be due to increase in temperature with the increased metabolism sufficient to cause a coagulation of protoplasm. One experiment in the present group suggests this result. A rat was exposed to an alternating circuit at 220-volt potential for thirty-five seconds. During that time the rectal temperature rose from 36.5° C. to 38° C.

Effect of Current upon the Blood.—A study of the changes in the blood of the rat, following electric shocks, was made by Miss Peabody. The animals examined were injured with alternating currents at 500 and 1,000 volt potentials. No constant change in the red blood cell count was found even in those animals in which hemorrhages in the spinal cord were known to have occurred.

A differential count showed that normally only a small number of the white blood cells of the rat were polymorphonuclear cells. A number were typical small lymphocytes; the great majority of the cells were larger and it was difficult either by the vital technic or in Wright's stain to differentiate the large lymphocytes from cells of the monocyte series. It seemed sufficient to divide the white cells into two groups, polymorphonuclear and mononuclear. There was a well-marked increase in white blood cells following the shock and the ratio of polymorphonuclear cells was increased. More degenerating white blood cells were found in smears. The leukocytosis appeared within two and a half hours following the injury.

Plans for Further Studies

This report gives little information concerning the problem which was of primary interest in planning and carrying out this experimental work—namely, changes produced in the central nervous system by electric currents. The reason for this is at once obvious, for a considerable time is required to prepare and study the microscopic material. This work will be finished soon. A partial description of the hemorrhages in the nervous system has already been given and this subject will be elaborated further.

Sufficient sections of the central nervous system have already been prepared to suggest that severe damage to the nerve cells is produced. At autopsy the central nervous system was removed at once and fixed in 95 per cent. alcohol. This fixation permits a study of nerve cell pathology. It is believed that this method of fixation was adequate to permit reliable statements to be made with some assurance concerning actual changes in the nerve cells. The sections are stained with thionin and with hematoxylin and eosin. It is hoped that a statement can be made in reference to each rat, as to whether the changes in the nervous system were sufficient to account for the death or the abnormalities seen following the shock. This constitutes a considerable technical problem.

Another extremely important question demands further investigation. Urquhart believes that the respiratory failure is due to a temporary block in the central nervous system. Provided no cardiac damage has occurred, artificial respiration, if it is begun at once, should save all the animals in which breathing is suspended following the shock. The present experiments do not appear to support this theory of Urquhart's. It is realized, however, that the technic of artificial respiration was not perfect in the case of the rat. It is proposed to test this theory again in larger animals where adequate artificial respiration can be applied by means of intratracheal insufflation. Certainly it has been shown that hemorrhages occur in the central nervous system that are incompatible with life.

Summary

The rat is a convenient animal for studying the effect of electricity upon the central nervous system, since the heart recovers spontaneously from the ventricular fibrillation produced by the shock. It is believed that few if any deaths in this series were caused by cardiac failure. In such biologic experiments there are so many variable factors that it is impossible to standardize the lethal application of the current. Series of animals were studied after application of alternating and continuous circuits at 110, 220, 500, and 1,000 volt potentials. The time that the current was allowed to flow was varied in each group. The electrodes were applied to the top of the skull and to the base of the tail.

The mortality increased in proportion to the depth of the anesthesia. No sex differences in susceptibility to the current were found. Small young animals were less resistant than adults.

With circuits at 110 and 220 volts, more injuries were produced with alternating than with continuous current. With a circuit at 500-volt potential, the effects were equalized, but with a circuit at 1,000-volt potential it was clear that the continuous current produced greater injury than the alternating. This was particularly well demonstrated when the time of application was taken into consideration.

A number of rats in all these groups never breathed following the shock even though artificial respiration was employed for a considerable period. Many of the animals that survived showed a paralysis of the posterior portion of the body with the subsequent

development of incontinence and hematuria. This paralysis was more common with the alternating than with the continuous circuit. Some rats died during the first few hours from a hemorrhage in the cerebral ventricles. Many others recovered and appeared normal following the injury.

Characteristic abnormalities were found in each group shocked with the alternating and continuous circuits at different potentials. The continuous current often produced symptoms of central nervous system irritation, such as convulsions, priapism, or paralysis that tended to regress.

Hemorrhages were common following the contact with electricity, particularly with the alternating circuit. A large hemorrhage in the spinal cord was found in all the rats in which the posterior portion of the body was paralyzed.

The nerve cells also showed characteristic abnormalities.

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A NEW KATA-THERMOMETER FOR HOT ATMOSPHERES AND A SIMPLIFIED METHOD FOR COMPUTING*

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PRACTICAL experience has shown that one of the greatest uses of the kata-thermometer is as an anemometer. The instrument is frequently required to investigate the ventilation of hot enclosures where the air temperature may either be so high as altogether to preclude the use of the dry kata, or sufficiently high to make its cooling period inconveniently long. To meet the need for an instrument to measure the conditions in such hot enclosures, Leonard Hill has introduced the modified kata-thermometer here described.

While this paper was being completed, an account was published by Yaglou and Dokoff of the behavior of the ordinary kata with various air velocities at very high temperatures, including observations on the rate of *heating*. The heating power of the air as measured by the ordinary kata is likely to be of value only for measuring air velocity at temperatures over 105°F., for the same reason that its cooling power is difficult to use at temperatures above 92°F.: *i.e.*, with small differences of temperature between kata and air the times of heating or of cooling are very long. The high temperature kata is available for such purposes for all endurable air temperatures. Fuller reference will be made to this paper later on.

The new instrument has its bulbs made to the same gauges as are used in making the original body temperature kata and its stem has the same bore, but the amount of spirit in the bulb is reduced, so that the two points, 5°F. apart, marked on the stem to give the working range of the instrument, are at 125°F. and 130°, instead of at 95° and 100°F. The new instrument thus has a mean temperature 30°F. higher than that of the old one and consequently the value of θ, the temperature difference between the bulb and the surrounding air, is greater by this amount; this causes the time of cooling in air of any given room temperature and velocity to be considerably less for the new high temperature kata than for the original one, and enables the new instrument to operate in temperatures of over 100°F.

It must be noted that the values of cooling power indicated by this new instrument, though stated in millicalories per square centimeter per second, are not comparable with the cooling powers of the original kata in so far as the readings of that kata are standardized in terms of human com-

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fort and physiologic reactions. In order to avoid possible confusion, it would be well to record any observations made with the high temperature kata by subscripts to the symbols—*e.g.*, if θ and H describe temperature difference and cooling power for the low temperature kata, θ_2 and H_2 shall be the denominations when the high temperature kata is employed.

We have found that within the limits of accuracy of the technic employed, the original and the new instruments obey precisely the same laws of cooling and that, in fact, H/θ is replaceable by H_2/θ_2 in the relationships with velocity. The considerable practical advantage results, therefore, that the same formula and the same nomographs can be used with each instrument, provided a simple allowance is made for the displaced temperature range when the new kata is employed.

The particulars of the experiments which we undertook and of the subsequent calculations which we made to evaluate the laws of the new instrument and to bring them into comparison with all the previous work are too lengthy for publication,[1] but they are kept for reference at the National Institute for Medical Research, Hampstead, where they may be seen by anyone desiring to examine the evidence.

Experiments were carried out and:

1. The factor of the new kata was determined in a still air chamber and in a mercury calorimeter (1). The difference between the factor values as determined by these two methods is very similar to the difference that was found between the factors of the ordinary low temperature kata when so determined; this shows that there can be no great difference between the physical actions (such as convection currents) affecting the two instruments when cooling in still air.

2. Calculation showed that the new instrument has not a significantly lower water equivalent on account of the reduced quantity of alcohol.

3. Two hundred thirty-five observations were taken of the cooling times of the new kata in air moving at velocities of from 0 to 16 meters per second, the measured air velocities being obtained by a whirling arm method for the low velocities and by a calibrated anemometer in a wind tunnel for the high velocities.

A preliminary plot of the 235 new high temperature kata observations together with the 108 original standard kata observations (2) and the 124 subsequent observations (3) did not show to the eye any change in the law connecting the cooling power for each degree of temperature difference with air velocity when the higher working range of temperature was used; so all the data were pooled, giving a total of 467 observations, wherewith to confirm or improve the previous formulas. In the end, a more exact numerical computation was made of the differences in the behavior of the high temperature and the standard katas in the several parts of the range of velocity, and in this way the conclusion was reached that the differ-

[1] Very detailed analysis of the experimental observations in all their bearings was made by Miss E. M. Newbold assisted by Mr. J. W. Martin and Miss C. A. Thomas, and latterly by Mr. H. E. Soper, and in this paper only a bare summary of the results is indicated.

ences were too small for quantitative estimation.

The formula previously obtained for the 124 observations (3) was

$$H/\theta = 0.50803\sqrt{v} + 0.10551 \quad (1)$$

where H = cooling power in millicalories per second per square centimeter of cooling surface (= factor of instrument ÷ time of cooling)

θ = mean temperature difference between the kata bulb and surrounding air, in degrees centigrade

v = air velocity in meters per second

and this formula fitted the observations between the limits of velocity v = 0.3 to v = 5.2.

In the present investigation, in order to extend the range of applicability and increase the precision, best fitting lines and parabolas were fitted to successive portions of the plot of the 467 points from v = 0 to v = 16, and from these linked curves the values of H/θ against v shown in the second column of Table 1 were computed.[2] From the same detached formulas was also constructed the first nomograph of the two mentioned below.

It was thought that a single formula should be found to cover the entire range from v = 0 to v = 16; the type chosen was that which results from supposing that the thermometer has an internal resistance, leading to its surface temperature θ_s (above air) being less than its registering temperature θ (above air), and that the thermal flow from surface into air follows a law of the general form $(a + bv^n) \times \theta_s$. The equation for the fitted curve,[3] expressed in the above degrees

TABLE 1.—VARIATION IN VALUES OF H/θ BETWEEN PRESENT RESULTS (FORMULA C) AND PREVIOUS RESULTS (FORMULA 1)

AIR VELOCITY	PRESENT DETACHED VALUE	VALUE COMPUTED FROM FORMULA C	VARIATION FROM DETACHED VALUE[1]	VALUE COMPUTED FROM FORMULA 1	VARIATION FROM DETACHED VALUE[1]
m./sec.			%		%
0	0.270	0.270	0.0	.....	.....
0.1	0.326	0.329	+1.0	.....	.....
0.4	0.447	0.443	−0.8	0.427	−4.4
0.7	0.533	0.533	0.0	0.531	−0.4
1	0.610	0.610	0.0	0.614	+0.5
2	0.807	0.817	+1.2	0.824	+2.1
3	0.971	0.978	+0.7	0.985	+1.4
4	1.109	1.111	+0.2	1.122	+1.1
5	1.231	1.224	−0.6	1.241	+0.8
6	1.320	1.322	+0.2	.....	.....
9	1.551	1.556	+0.3	.....	.....
12	1.742	1.730	−0.7	.....	.....
15	1.895	1.866	−1.5	.....	.....
∞	.....	3.330	.....	.....	.....

[1] Calculated from the full working figures.

[2] When employing the ordinary kata, θ = 97.5°F. − air temperature. When employing the high temperature kata, θ = 127.5°F. − air temperature. θ is increased by 30°F. or by 16.7°C. and the cooling power H is increased in the same proportion in which θ has been increased, the ratio H_2/θ_2 remaining unchanged.

[3] This curve combines the equation $H = 3.33(\theta - \theta_s)$, attributing to the thermometer a conductivity of 3.33 millicalories per square centimeter per second per degree centigrade (say that of 1 mm. of alcohol in the direction of the heat flow from core to surface), with the equation $H = (0.294 + 0.453v^{4/5})\theta_s$, giving a still air emission of 0.294 from glass and a law with velocity varying as its 0.8 power instead of its 0.5 power as usually taken. Some experiments on the time of fall when the kata is dipped in mercury appeared to point to a conductivity in the neighborhood of 5.

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centigrade and meters per second units, is

$$\frac{H}{\theta} = \frac{2.16 + 3.33\ v^{4/5}}{8 + v^{4/5}}$$

$$\therefore\ v = \left(\frac{H/\theta - 0.27}{3.33 - H/\theta}\right)^{5/4} \qquad (C)$$

Expressed in degrees Fahrenheit and feet per minute units, this becomes

$$\frac{H}{\theta'} = \frac{1.2 + 1.85\ (v'/197)^{4/5}}{8 + (v'/197)^{4/5}}$$

$$\therefore\ \frac{v'}{197} = \left(8\,\frac{H/\theta' - 0.15}{1.85 - H/\theta'}\right)^{5/4} \qquad (C')$$

The values given by this through formula are shown in column 3 of Table 1, together with their percentage differences from the detached values in column 2.

From formula C′ are computed the values of H/θ' against v′ given in Table 2 which are also the values needed in the construction of the second of the two nomographs mentioned below.

In order to compare present findings with past findings, in column 4 of Table 1 are shown the values given by the nomograph previously published (3) and their percentage differences from the values in column 2. It will be seen that the nomograph is accurate for the portion of the curve served.

Besides the formulated, or mean, values, we require also to know the character of the departures of the individual observations, from these values, as shown in our detailed data. The differences may reside in the values attributed to H/θ or in the values attributed to v; appeal to the chart cannot decide which. Assuming that the differences reside chiefly in the measurements of v, it appears, as the result of our calculations, that the errors in measuring air velocities by the kata-thermometer average a trifle over 10 per cent. of their value, plus or minus.

Two nomographs have been made:[4]

1. A nomograph with logarithmic scales and divided in metric and British units, giving accurate readings of velocities from 0.02 to 5.4 meters per second and of temperatures from 0° to 34°C. This nomograph is very similar to that published in the work referred to above, but has the advantage that it includes the low velocity range.

2. A double nomograph divided in British units and designed for field use by engineers and others. It consists of five scales. From the points on the first scale of factors and the second scale of seconds is found by a thread or straight edge the point on the third scale of cooling power, and from this point and the point on the fourth scale of room temperature is found the point on the fifth scale of air velocity. (Fig. 1.)

Either nomograph can be used with the new high temperature kata. In this case, since the kata has been raised 30°F. (16.7°C.) in temperature,

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The formula C is difficult to calculate and the simpler formula $H/\theta = \sqrt{0.29(0.26 + v)}$ will give the same values, within 2 per cent., for values of v from v = 0.1 to v = 6. Its inversion is $v = (H/\theta)^2/0.29 - 0.26$. This formula is purely empirical.

[4] The first of these nomographs has not been published as it is so very similar to that shown in an earlier report (3); the second may be obtained from Messrs. J. Hicks, 8, Hatton Garden, London, E. C.

TABLE 2.—RELATIONSHIP BETWEEN VALUES OF H/θ' AND AIR VELOCITY

H = cooling power in millicalories per second per square centimeter of cooling surface = factor of instrument ÷ time of cooling.

θ' = mean temperature difference between kata bulb and surrounding air, in degrees Fahrenheit.

v′ = air velocity in feet per minute.

v′	H/θ'	v′	H/θ'	v′	H/θ'	v′	H/θ'
v′ = 0 to 800							
0	0.150	200	0.341	400	0.457	600	0.547
10	.169	210	.348	410	.462	610	.551
20	.183	220	.354	420	.467	620	.555
30	.196	230	.361	430	.472	630	.559
40	.207	240	.367	440	.477	640	.563
50	.218	250	.373	450	.481	650	.567
60	.228	260	.380	460	.486	660	.571
70	.238	270	.386	470	.491	670	.575
80	.247	280	.392	480	.495	680	.578
90	.256	290	.398	490	.500	690	.582
100	.265	300	.403	500	.505	700	.586
110	.274	310	.409	510	.509	710	.590
120	.282	320	.415	520	.513	720	.593
130	.290	330	.420	530	.518	730	.597
140	.298	340	.426	540	.522	740	.601
150	.305	350	.431	550	.526	750	.604
160	.313	360	.436	560	.531	760	.608
170	.320	370	.442	570	.535	770	.611
180	.327	380	.447	580	.539	780	.615
190	.334	390	.452	590	.543	790	.618
200	.341	400	.457	600	.547	800	.621
v′ = 800 to 3,200							
800	0.621	1,400	0.788	2,000	0.905	2,600	0.994
850	.638	1,450	.799	2,050	.913	2,650	1.000
900	.654	1,500	.810	2,100	.921	2,700	1.007
950	.670	1,550	.821	2,150	.929	2,750	1.013
1,000	.685	1,600	.831	2,200	.937	2,800	1.019
1,050	.699	1,650	.841	2,250	.945	2,850	1.025
1,100	.713	1,700	.851	2,300	.952	2,900	1.031
1,150	.726	1,750	.860	2,350	.959	2,950	1.037
1,200	.740	1,800	.870	2,400	.967	3,000	1.042
1,250	.752	1,850	.879	2,450	.974	3,050	1.048
1,300	.764	1,900	.888	2,500	.980	3,100	1.053
1,350	.776	1,950	.896	2,550	.987	3,150	1.059
1,400	.788	2,000	.905	2,600	.994	3,200	1.064

the scale readings of temperature upon the chart must be similarly increased, to keep the same differences, θ. It will come to the same thing if like amounts are *deducted from the thermometer reading*.

The original nomograph published by Messrs. J. Hicks, makers of the

kata-thermometer, and now in use is found to conform to the new formula within the limits of accuracy of the instrument at velocities below 2.5 meters per second (500 feet per minute) and so its use may safely be continued by those who have it for measuring such velocities. At the low velocities found in inhabited enclosures, there are no serious differences between velocities calculated by the older formula and those calculated by the newest formula.

In a paper by C. P. Yaglou and Kroum Dokoff (4), received by us since the foregoing was written, attention is drawn to the want of experimental observations in calibration of the ordinary kata for use for room temperatures over 100°F.—that is,

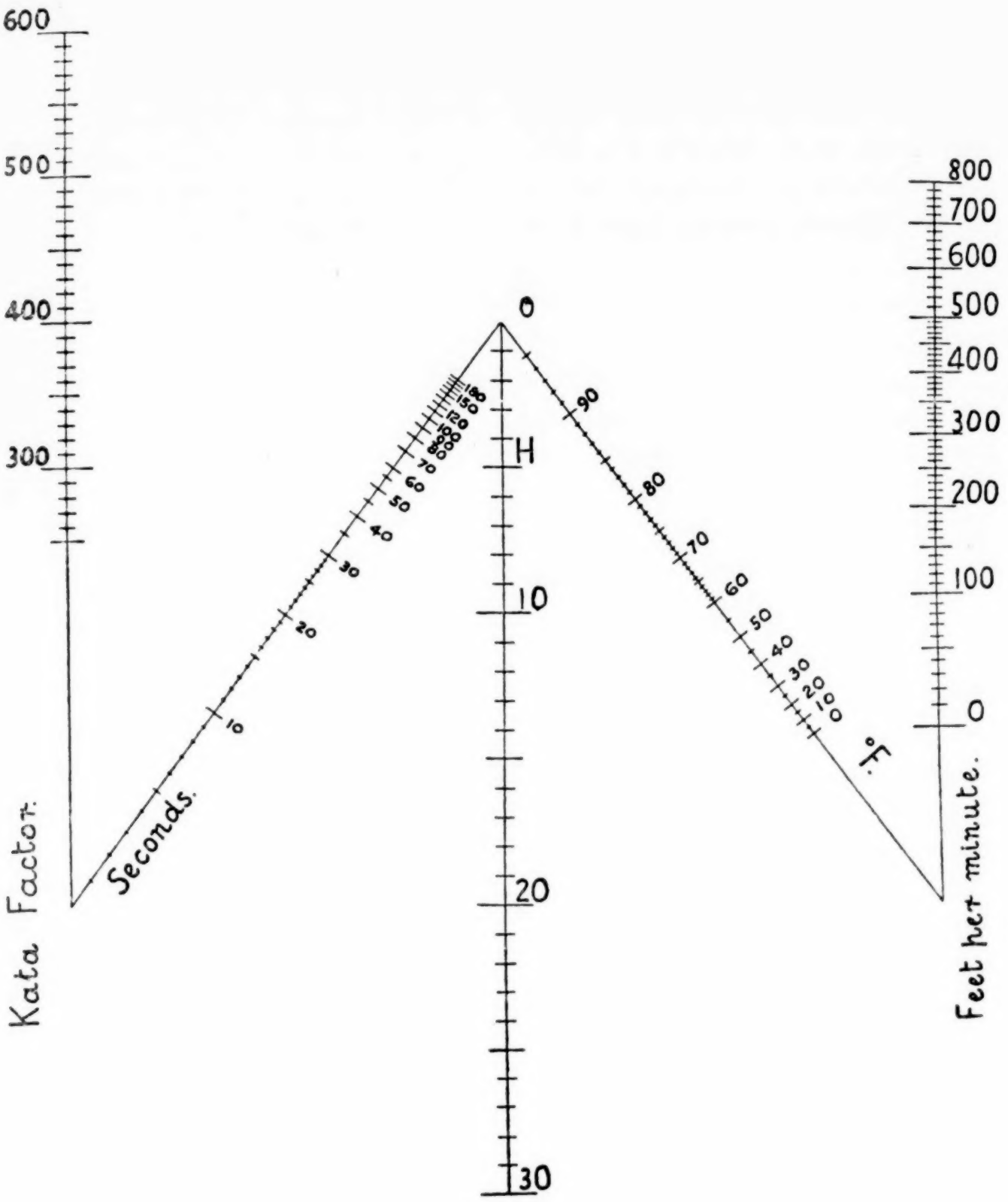

FIG. 1.—Nomograph for high temperature kata.

for use as an instrument for measuring the *heating* power of the still or moving air upon the body. The paper describes the results of a great many observations that were taken of the behavior of the ordinary kata, both dry and wet, using temperature ranges from 35°F. to 165°F. for dry kata and 32°F. to 112°F. for wet kata, for air velocities held at 0, 20, 40, 75, 100, 220, 440, 660 feet per minute, and at relative humidities varying from 2 to 100 per cent.

In the case of the dry kata, the resulting plots of H against θ for each air velocity show a bending of the line outward for the smaller air velocities, thus indicating that the cooling (or heating) of the bulb increases rather more rapidly than in true proportion with the temperature difference. The "chimney" effect, if such it is, is hardly discernible for air velocities greater than 0.5 meter per second and our observations below v = 0.5 are insufficient in number to confirm the finding. A similar effect is found for room temperatures both below and above the kata temperature; in the latter case a downflow of cooler air, past the bulb, would be the supposition. In either case it is necessary also to suppose that the effect increases faster than it would by proportionality with θ. According to the graph, when the air velocity is as low as 20 feet per minute (0.1 meter per second) the effect will add some 8 per cent. to the reading of the instrument, supposed correct at 65°F. room temperature, when the temperature is as low as 35°F.

These experiments appear to confirm the view that excepting where the temperature difference is out of the ordinary, say over 60°F., and air currents are very light, say under 20 feet per minute (0.1 meter per second), there is no occasion in practical work to assume greater refinement than that given by a linear law connecting H with θ.

TABLE 3.—COMPARISON OF VALUES OF H/θ FROM YAGLOU-DOKOFF CHART WITH VALUES COMPUTED FROM FORMULA C

AIR VELOCITY	VALUE FROM YAGLOU-DOKOFF CHART	VALUE COMPUTED FROM FORMULA C	DIFFERENCE[1]	MAXIMUM ERROR IN READING
ft./min.			%	
0	0.273	0.270	+1.1	±2.4
20	.335	.330	+1.3	±2.0
40	.366	.373	−1.8	±1.8
75	.448	.437	+2.4	±1.5
100	.471	.477	−1.4	±1.4
220	.650	.638	+1.9	±1.0
440	.867	.858	+1.0	±0.7
660	1.078	1.041	+3.5	±0.6

[1] Calculated from the full working figures.

It is in measuring cooling power and especially in deducing air velocities when room temperature is near the kata or body temperature that errors are most troublesome, and it was to eliminate such sources of error that the present kata, working at a higher temperature than body temperature, was devised. The observations made with this hot bulb kata show that the same formula covers the behavior of both warm bulb and hot bulb instruments. It was necessary in our case to obtain a graduation formula to cover the whole experience, in the light of which the several constituent groups of observations could be examined.

The authors of the paper do not attempt to formulate the relation of H and v for given θ, even for so limited a range of velocities as 0 to 660 feet per minute (0 to 3.35 meters per second); and our attempt to obtain a formula that will need no qualifications either for small velocities up to 20 feet per minute or for large velocities up to 3,300 feet per minute may suggest a reexamination by Yaglou and Dokoff of their very extensive experimental data to elucidate the law and its refinements for large values of the temperature difference θ.

As far as could be done by measurements of a chart, we have compared the results obtained by Yaglou and Dokoff with our formulas for the relation of H/θ to air velocity. We find that at temperature 65°F. their differences are little over those which might be expected to arise from chart measurements (see Table 3).

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3. Hill, L., Angus, T. C., and Newbold, E. M.: Further Experimental Observations to Determine the Relations between Kata Cooling Powers and Atmospheric Conditions. This Jour., 1928, *10*, 391.
4. Yaglou, C. P., and Dokoff, K.: Calibration of the Kata-Thermometer over a Wide Range of Air Conditions. *Ibid.*, 1929, *11*, 278.

BOOK REVIEW

THE DIAGNOSIS OF HEALTH. By *William R. P. Emerson*, M.D., Medical Consultant in Physical Fitness at Dartmouth College; President, Nutrition Clinics, Inc.; Author of "Nutrition and Growth in Children." Cloth. Pp. xiv, 272 with index and illustrations. New York: D. Appleton Co., 1930.

This book is a full and simple summary of the author's technic for being well and keeping well. It contains nothing either mysterious or weighty. It will be of more use to school nurses and teachers in schools and colleges than to persons with a large amount of technical training. It would seem to the reviewer that the material which deals with personality and with what is called health intelligence, could well be used in the cases of many subnormal persons in industry. There are aspects of the book, such as the emphasis upon weight as an index of physical fitness, to which exception may be taken, but on the whole the material presented is useful and stimulating, and where overemphasis occurs it deals with matters not profoundly important for the success of the program outlined.—*Cecil K. Drinker.*

BOOKS RECEIVED

Books received are acknowledged in this column, and such acknowledgment must be regarded as a sufficient return for the courtesy of the sender. Selections will be made for review in the interest of our readers and as space permits.

PRACTICAL PSYCHOLOGY AND PSYCHIATRY. By *C. B. Burr*, M.D., Late Medical Director Oak Grove Hospital (Flint, Mich.) for Mental and Nervous Diseases; Member of the American Psychiatric Association, etc. Sixth edition, revised and enlarged. Cloth. Pp. 378 with index and illustrations. Philadelphia: F. A. Davis Co., 1930.

PRACTICAL MASSAGE AND CORRECTVE EXERCISES WITH APPLIED ANATOMY. By *Hartvig Nissen*, Late President of Posse Normal School of Gymnastics, Superintendent of Hospital Clinics in Massage and Medical Gymnastics, Former Director of the Swedish Health Institute, Washington, D. C., etc. Fifth edition, revised and enlarged by Harry Nissen, President, Posse-Nissen School of Physical Education, Boston, Mass. Cloth. Pp. 271, with index and 72 original halftone and line engravings. Philadelphia: F. A. Davis Co., 1929.

THE COMMON HEAD COLD AND ITS COMPLICATIONS. By *Walter A. Wells*, A.M., M.D., F.A.C.S., Professor of Oto-Laryngology, Georgetown University, Washington, D.C. With an introduction by Hugh S. Cumming, M.D., Surgeon General, United States Public Health Service. Cloth. Pp. xiii, 225 with illustrations. New York: The Macmillan Co., 1929.